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RESEARCH MEMORANDUM

SCREAMING TENDENCY OF THE GASEOUS-HYDROGEN - LIQUID-OXYGEN PROPELLANT COMBINATION

By Louis Baker, Jr. and Fred W. Steffen

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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SCREAMING TENDENCY OF THE GASEOUS-HYDROGEN - LIQUID-OXYGEN PROPELLANT COMBINATION

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SUMMARY

An exploratory study of the screaming tendency of the gaseous-hydrogen - liquid-oxygen propellant combination was made in 200-pound-thrust rocket engines. Four injector classes, a total of 12 different configurations, were tested in chamber lengths from 3 to 24 inches over the usable mixture-ratio range. Screaming was sensed by a high-frequency-response pressure transducer.

Longitudinal oscillations with amplitudes below 15 pounds per square inch were obtained with every injector in 12- to 24-inch chamber lengths. Chamber lengths of 3 and 6 inches occasionally produced very high-frequency oscillations of unknown mode.

Only three injector configurations produced high-amplitude, up to 60 pounds per square inch, longitudinal oscillations. Spray-photograph studies indicated that these injector configurations produced good atomization and mixing of the propellants close to the injector face. Spray photographs of nonscreaming configurations indicated that the screaming waves may have been attenuated by a region of cool hydrogen gas near the injector face.

The results indicate that the gaseous-hydrogen - liquid-oxygen propellant combination may not have the marked screaming tendency of some all-liquid combinations.

INTRODUCTION

High-frequency combustion oscillations (screaming) are a serious problem in the development of liquid-oxygen - hydrocarbon rocket engines. Screaming, particularly in transverse modes, causes excessive heat transfer and burnouts. The screaming tendencies of high-energy propellant combinations, especially those that use hydrogen as the fuel, are not known. A preliminary study of the streaming tendency of the gaseous-hydrogen - liquid-oxygen propellant combination was therefore undertaken.

The work was carried out in rocket engines of 200 pounds nominal thrust. While such equipment does not represent the size of rocket engines to be developed ultimately, successful correlations have previously been made between screaming in the longitudinal mode in small-scale engines and screaming in the transverse mode in large-scale engines. These correlations suggest that an initial small-scale study can produce results that indicate the screaming tendency of a propellant-injector combination.

The experimental program was conducted with gaseous hydrogen rather than liquid hydrogen since in any long-range missile application, hydrogen would be used as the regenerative coolant. The hydrogen would then enter the injector manifold above its critical temperature.

A previous study of gaseous-hydrogen - liquid-oxygen combustion performance, made at the Lewis laboratory and reported in reference 1, did not show any clearly discernible screaming. One streak photograph showed some oscillations; several burnouts suggested the possible presence of screaming oscillations. The performance of seven single-element injectors was reported in reference 1. In every case, however, the hydrogen flow from the injector into the chamber was sonic or nearly sonic. Therefore, the present research includes a study of the effect of hydrogen-injection velocity on screaming.

Two series of impinging-jet injectors, a parallel-jet injector, a series of concentric-tube injectors, and two radial-jet injectors were designed and tested. In all cases the internal combustion-chamber diameter was 2 inches. Chamber lengths from 3 to 24 inches were studied.

Screaming was sensed by a water-cooled, strain-gage-type pressure transducer having a very high natural frequency.

The characteristic velocity performance and the results of heat-transfer measurements obtained during this study are reported in detail in reference 2.

APPARATUS AND PROCEDURE

Rocket Installation

The 200-pound-thrust rocket installation was similar to one described in reference 1. Hydrogen was stored in high-pressure cylinders and delivered to the engine at ambient temperature. Liquid oxygen was stored in a tank surrounded by liquid nitrogen (-320° F) and pressurized with high-pressure helium. The oxygen was delivered to the engine at liquid-nitrogen temperature to minimize gas formation before injection.

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The combustion chambers had inside diameters of 2 inches and lengths that varied from 3 to 24 inches. The high-frequency-response pressure transducer was flush mounted in a 2-inch long copper segment located adjacent to the injector. The center of the diaphragm of the transducer was thus located 1 inch from the injector face for all runs. A 2-inch long water-cooled segment was located adjacent to the nozzle and was used to measure the heat-transfer rate from the chamber gases to the chamber walls. A copper water-cooled convergent nozzle with a nominal throat diameter of 0.75 inch was used.

Injectors

The injectors studied in this report are shown schematically in figures 1 to 4.

The series I, impinging-jet injectors (fig. 1) had two impinging jets of liquid oxygen; the hydrogen entered from behind the jets through interchangeable plates. Four different plates were used to vary both the hydrogen-injection velocity and distribution.

The series II, impinging-jet injectors (fig. 2) had one axial liquid-oxygen jet and two impinging hydrogen jets per element. Single-element injectors having impingement angles of 0° (parallel jets) and 40° were studied. A four-element and a nine-element injector were also studied.

The concentric-tube injector (fig. 3) was made in a nine-element design.

The radial liquid-oxygen-jet injectors (fig. 4) were designed to promote combustion near the injector face. Two of the hydrogen-injection plates used with series I injectors were also used with the radial-jet series.

Instrumentation

A venturi meter and a rotating-vane flow meter were used to measure the gaseous-hydrogen and liquid-oxygen flows, respectively. Steady-state chamber and propellant-injection pressures were measured with strain-gage-type pressure transducers. Propellant and cooling-water temperature measurements were made with thermocouples.

The high-frequency chamber-pressure oscillations were measured by means of a water-cooled, strain-gage-type pressure transducer having a natural frequency in excess of 20,000 cycles per second. A block diagram of the circuit used with the transducer is given in figure 5. Both of the oscilloscope beams swept horizontally 60 times per second. The duration of each sweep was varied between 0.0015 and 0.0025 second. A film speed of 60 inches per second was used. A typical film sequence is shown in figure 6. The net effect of the combined sweep and film motion was to provide 0.0015- to 0.0025-second samples of both the transient pressure and the 1000-cycle timing trace every 1/60 of a second. Therefore, the time required for each of the two beams to make one sweep was equal even though the transient pressure trace was longer than the 1000-cycle timing trace. This fact was considered in computing the experimental frequencies.

The condenser C (fig. 5) formed a high-pass filter so that the oscilloscope trace level did not depend upon the steady-state chamber pressure. It was thus possible to use a high amplification without the danger of driving the trace offscale during high-pressure runs. The amplification factor changed only very slightly from one run to the next.

Photographs were taken of the spray produced by substituting water and air for the oxygen and hydrogen and removing the combustion chamber. The spray photographs were taken with a 1/30,000-second electronic flash located behind a diffuser screen directly behind the spray. Water and airflows were measured by calibrated rotameters.

Operating Procedure and Data Reduction

The moving-picture camera was coupled electrically to the fuel fire valve so that both operated simultaneously. The duration of the runs varied from 2.5 to 5.0 seconds. Chamber pressures from 150 to 400 pounds per square inch, gaseous-hydrogen flow rates from 0.04 to 0.13 pound per second, and liquid-oxygen flow rates from 0.3 to 0.6 pound per second were used.

The 35-millimeter film strip from each run was examined. Measurements were made of the frequency and amplitude of the transient pressure from the frame showing the maximum amplitude. Only frames corresponding to steady-state engine operation were considered.

Theoretical Screaming Frequency

Theoretical frequencies were calculated using the following equations for the fundamental notes in an organ pipe (ref. 3):

Longitudinal frequency $$L = \frac{c}{2l}$$

First transverse tangential frequency $$T = \frac{c}{2} \frac{0.586}{r}$$

where l and r are the chamber length and radius, respectively, and c is the velocity of sound in the burned gases.

Values of the velocity of sound in the adiabatic combustion products as a function of mixture ratio are shown in figure 7. These were calculated according to the method outlined in reference 4 for a chamber pressure of 600 pounds per square inch with liquid hydrogen at the normal boiling point. The values apply reasonably well for the conditions encountered in this investigation.

RESULTS AND DISCUSSION

Acoustic Oscillations

The runs made with each injector - chamber-length combination and the runs with peak-to-peak oscillation amplitudes exceeding 15 pounds per square inch (hereafter called high amplitude) are given in table I. It will be noted immediately that high-amplitude or screaming oscillations occurred with only three of the injector configurations. These were the nine-element, series II, impinging-jet injector, the 10-center-hole radial-jet injector, and the 45-center-hole radial-jet injector. The operating conditions during these high-amplitude runs together with the theoretical screaming frequencies for the longitudinal mode are shown in table II. Some of the film strips from which these experimental screaming frequencies were obtained are shown in figure 8. These frequencies did not persist but appeared and disappeared randomly throughout the run. Although the measured frequency generally corresponded to the theoretical frequency, the oscillations were sometimes very irregular (fig. 8) and made frequency measurement very difficult.

Low-amplitude longitudinal oscillations appeared to some extent in almost every run made in chamber lengths between 12 and 24 inches. Film strips from five typical runs made with the series I, impinging-jet injectors are shown in figure 9. Runs with two different chamber lengths and widely different mixture ratios are presented. The theoretical frequency values for the lowest longitudinal mode show good agreement with the experimental frequencies. The peak-to-peak amplitude of the oscillations ranged between 0 and 15 pounds per square inch. As in the case of the high-amplitude screaming oscillations, the oscillations did not remain well defined like those shown in figure 9, but appeared and disappeared randomly throughout the runs.

Large changes in hydrogen-injection velocity were made by changing the number of hydrogen outlet holes in the series I, impinging-jet injectors. However, no high-amplitude oscillation screaming was noted with any of the series I, impinging-jet configurations.

Unclassified Oscillations

Runs made in the 3- and 6-inch chambers did not have oscillations in the frequency range corresponding to the lowest longitudinal mode. In several runs, very high-frequency irregular oscillations were recorded. An example is shown in figure 10. It is not certain whether this is a higher harmonic of either a transverse or a longitudinal mode, or whether the transducer was excited in some way.

Runs made with the radial-jet injector in 3-inch chamber lengths showed persistent oscillations having a frequency of about 1250 cycles per second and amplitudes up to 65 pounds per square inch peak-to-peak. The lowest theoretical longitudinal frequency, 10,000 cycles per second, and the lowest theoretical transverse frequency, 15,000 cycles per second, are both well above the experimental value. The 1250-cycle-per-second oscillation is apparently not associated with the acoustics of the chamber but may involve the propellant flow (chugging). A typical pressure trace is shown in figure 11.

Driving and Damping Mechanisms

An inspection of water-air spray photographs of the injectors generally shows that the injectors with which high-amplitude oscillations occurred produced good atomization and mixing close to the injector face. Spray photographs for injectors with which high-amplitude oscillations occurred are shown in figure 12. Spray photographs of injectors with which high-amplitude oscillations did not occur are shown in figure 13. These results suggest that a local region of high heat release per unit combustion volume is required to drive screaming combustion waves. The series I and II injectors which showed marked screaming tendencies with the liquid-hydrocarbons - liquid-oxygen propellant combination (refs. 5 and 6) showed little screaming tendency with the gaseous-hydrogen - liquid-oxygen combination used in this investigation. This may be attributed to (1) the aforementioned local region of high heat release per unit volume, and (2) the greater sensitivity of vaporization and mixing processes to velocity and pressure disturbances in the all-liquid propellant case. In support of cause (1) it can be argued that the local propellant concentration prior to combustion can be appreciably greater for the all-liquid propellants than for the rarefied gaseous-hydrogen - liquid-oxygen propellants. With reference to cause (2) it would seem that drop shattering, vaporization rates, and mixing rates are more significantly affected in a biliquid propellant system, particularly, because the sprays of both liquids are affected simultaneously. The two causes cannot be completely divorced, because they affect each other.

Damping may also have influenced the results. Some injectors, which did not promote screaming, gave performance values in short chambers as

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high as those that did promote screaming. For example, the data of figure 14, taken from reference 2, show that with a 3-inch chamber length the performance of the nine-element, concentric-tube injector was as high as that of either the nine-element, series II or the radial-jet injector. Although none of these injectors screamed in 3-inch chambers, both the nine-element, series II and radial-jet injectors screamed in 12-inch chambers while the nine-element, concentric-tube injectors did not. The apparent heat-release rates, as determined by the performance of the 3-inch chambers, were the same in all three cases. However, differences in damping may have resulted from a region of relatively cold hydrogen gas near the injector face. The concentric-tube injector and, in fact, most of the injector configurations with which no screaming was observed, did not mix hydrogen and oxygen effectively until the propellants were a considerable distance downstream of the injector face (see fig. 12(b)). It seems possible that a region of cold hydrogen gas at the end of the chamber increased the dissipation of the screaming waves. Such an effect was discussed in reference 5.

Effects of Screaming on Heat Transfer

In order to give a consistent set of data, the heat-transfer results were normalized to 300 pounds per square inch according to the formula

$$Q_{300} = Q\left(\frac{300}{P_c}\right)$$

where Q is the heat-transfer rate and P_c the chamber pressure. The heat-transfer results for the series II, nine-element, impinging-jet injector and the radial-jet injector are shown in figure 15 with the high-amplitude screaming runs indicated by solid symbols. The results for a set of series I (nonscreaming) injectors are included for comparison. No effect of screaming amplitude is apparent on the measured heat-transfer rate. This is probably due to the random appearance and disappearance of the oscillations. No runs were observed in which oscillations continued for more than a few tenths of a second at a time. The measured heat-transfer rate represents only an average value for the latter half of the run and is subject to large experimental scatter.

SUMMARY OF RESULTS

The preliminary nature of the data concerning the screaming tendency of the gaseous-hydrogen - liquid-oxygen propellant combination precludes any generalized conclusions. The data imply, however, that rocket engines using this propellant combination may not have the marked screaming tendency of an all-liquid system. Spray photographs of injectors used with the relatively few configurations that caused high-amplitude screaming suggest that the driving force was supplied by a region of high heat release per unit volume. On the other hand, similar characteristic velocity performance of both screaming and nonscreaming configurations suggests that the driving forces may have been outweighed by strong damping forces in the nonscreaming configurations. These damping forces may have been caused by regions of unburned hydrogen near the injector face which attenuated the screaming waves.

Large changes in hydrogen-injection velocity were made with one series of injectors and had no effect in promoting screaming.

Probably, because of the random appearance and disappearance of the oscillations, there appeared to be no effect of screaming amplitude on the measured heat-transfer rate.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 21, 1958

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1. Auble, Carmon M.: A Study of Injection Processes for Liquid Oxygen and Gaseous Hydrogen in a 200-Pound-Thrust Rocket Engine. NACA RM E56I25a, 1957.

2. Heidmann, M. F., and Baker, L.: Performance of Various Hydrogen-Oxygen Injection Methods in a 200-Pound-Thrust Rocket Engine. NACA RM E58E21, 1958.

3. Smith, R. P., and Sprenger, D. F.: Combustion Instability in Solid-Propellant Rockets. Fourth Symposium (International) on Combustion, Williams & Wilkins Co., 1953, pp. 893-906.

4. Huff, Vearl N., Gordon, Sanford, and Morrell, Virginia E.: General Method and Thermodynamic Tables for Computation of Equilibrium Composition and Temperature of Chemical Reactions. NACA Rep. 1037, 1951. (Supersedes NACA TN's 2113 and 2161.)

5. Feiler, Charles E.: Effect of Fuel Drop Size and Injector Configuration on Screaming in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane. NACA RM E58A20a, 1958.

6. Heidman, M. F., and Auble, C. M.: Injection Principles from Combustion Studies in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane. NACA RM E55C22, 1955.

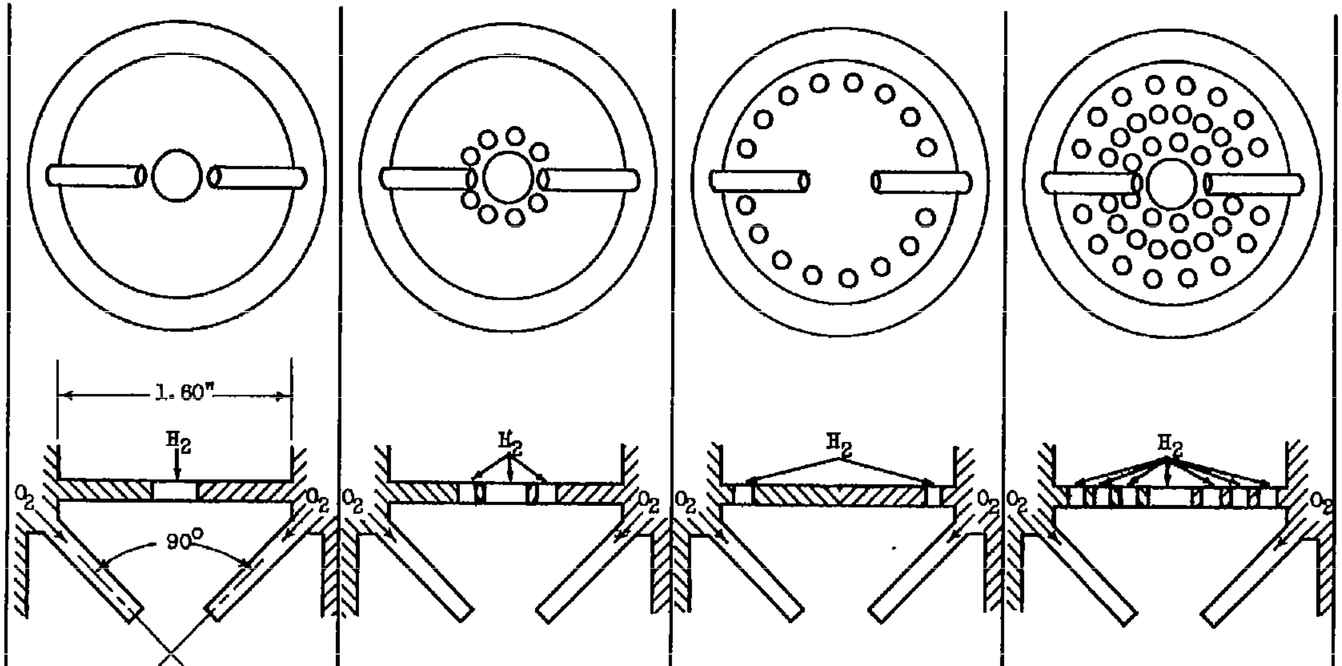
TABLE I. - CONFIGURATIONS AND SCREAMING RECORDS

	Chamber length, in.	Total runs	Number of runs having high-amplitude[a] longitudinal oscillations
Series I, impinging-jet injectors (fig. 1)			
One center hole	12	12	0
10 Center holes	16	9	0
16 Peripheral holes	14	13	0
	22	5	0
45 Holes	3	4	0
	24	12	.0
Series II, impinging-jet injectors (fig. 2)			
Single element, 0°	12	3	0
Single element, 40°	12	3	0
Single element, off-center	12	4	0
Four element	12	8	0
Nine element	3	5	0
	6	6	0
	12	11	2
Concentric-tube injector (fig. 3)			
Nine element	3	5	0
	12	11	0
Radial-jet injectors (fig. 4)			
10 Center holes	3	4	0
	12	9	3
	24	6	3
45 Center holes	12	4	0
	16	4	1

[a]Amplitude exceeding 15 lb/sq in. peak-to-peak.

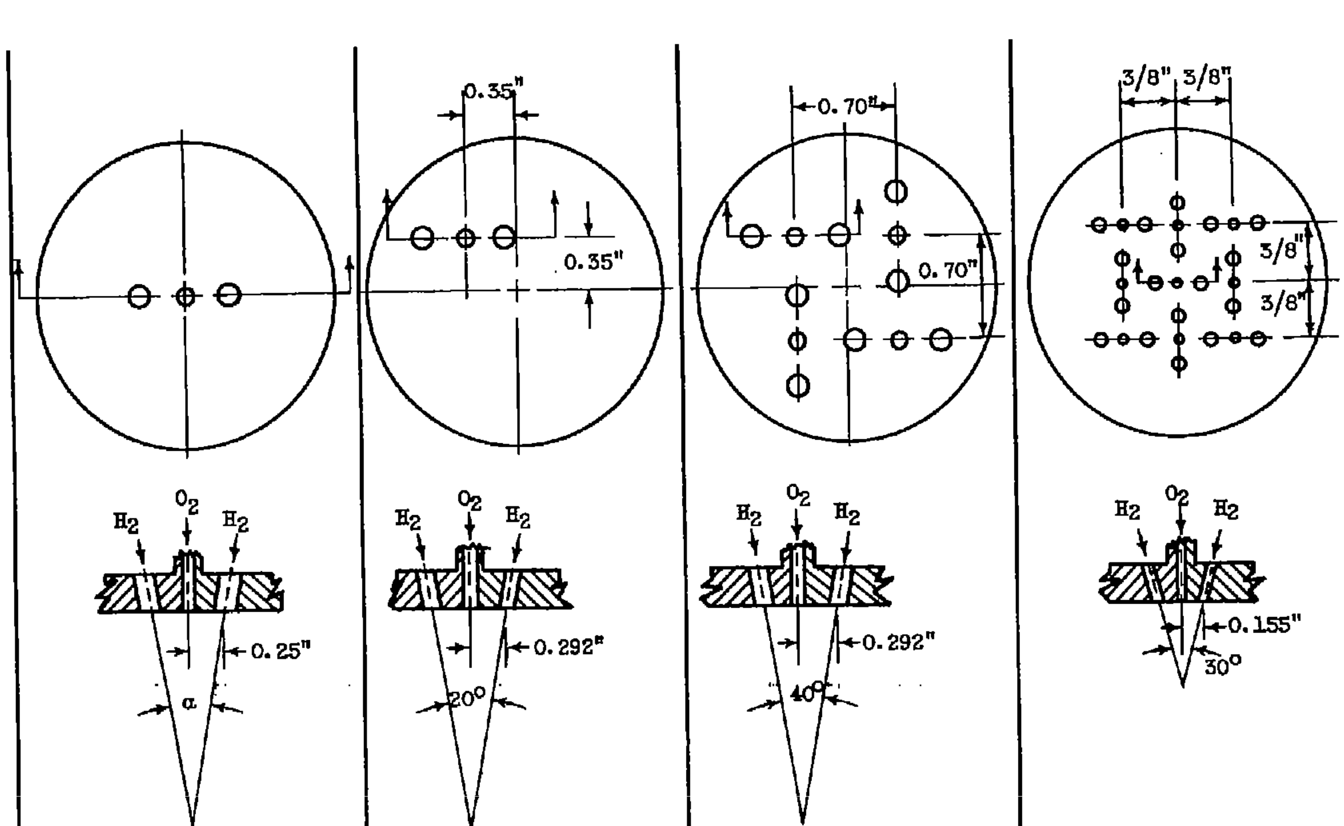
TABLE II. - SUMMARY OF RESULTS OF RUNS SHOWING HIGH-AMPLITUDE LONGITUDINAL OSCILLATIONS

Run	Mixture ratio, o/f	Chamber pressure, lb/sq in.	Chamber length, in.	Frequency, cps		Maximum amplitude, lb/sq in.
				Theoretical (fundamental longitudinal)	Experimental	
Nine element, series II injector						
192	3.11	273	12	2890	3530	37
196	6.92	326	12	2450	3980	62
Radial-jet injectors; 10 center holes						
262	4.33	353	12	2740	3200	16
261	4.33	269	12	2740	3150	32
267	4.32	325	12	2740	2800	40
275	3.52	273	24	1420	1430	16
280	6.64	270	24	1240	1400	30
281	6.51	357	24	1240	1400	53
Radial-jet injector; 45 center holes						
171	7.44	277	16	1800	3900	38



	Injection plate 1 (One center hole)	Injection plate 2 (10 Center holes)	Injection plate 3 (16 Peripheral holes)	Injection plate 4 (45 Holes)
Total flow areas, sq in.				
Liquid oxygen	0.0124	0.0124	0.0124	0.0124
Hydrogen	0.0356	0.1868	0.1963	0.6286
Hydrogen inlet velocity, ft/sec	3820	860	820	255

Figure 1. - Series I, impinging-jet injectors.



	Single element; angle of attack, 0° and 40°	Single element offcenter	Four element	Nine element
Total flow areas, sq in.				
Liquid oxygen	0.0075	0.0075	0.0302	0.0113
Hydrogen	0.0433	0.0433	0.1731	0.0951
Hydrogen inlet velocity, ft/sec	3293	3293	925	1645

Figure 2. - Series II, impinging-jet injectors.

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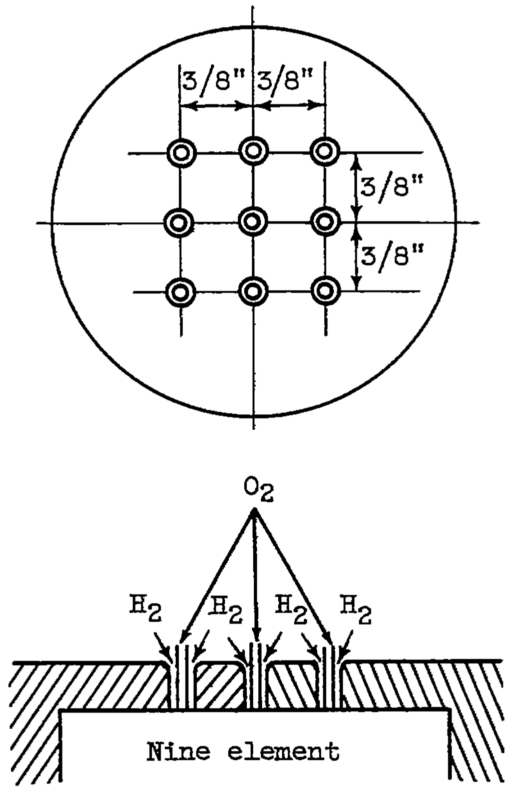
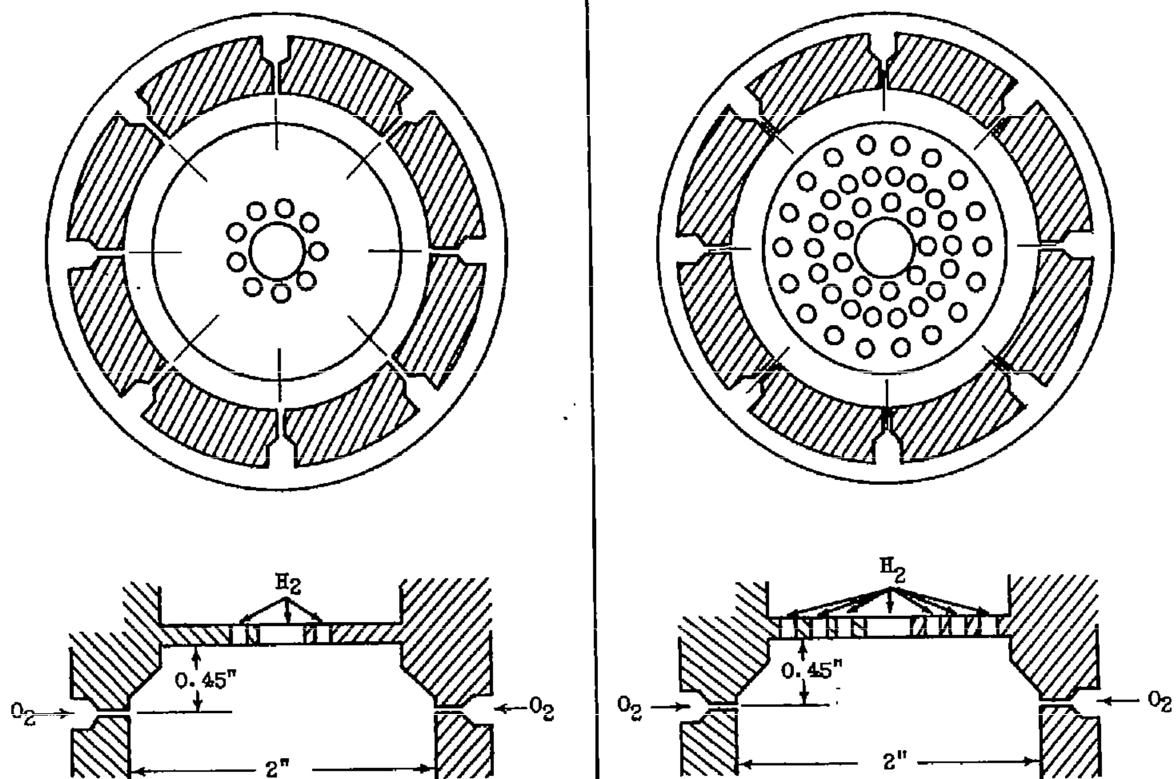


Total flow areas, sq in.	
Liquid oxygen	0.0113
Hydrogen	0.0939
Hydrogen inlet velocity, ft/sec	1675

Figure 3. - Nine-element concentric-tube injector.



Injection plate 2
(10 Center holes)

Injection plate 4
(45 Holes)

	Injection plate 2	Injection plate 4
Total flow areas, sq in.		
Liquid oxygen	0.0136	0.0136
Hydrogen	0.1868	0.6286
Hydrogen inlet velocity, ft/sec	860	255

Figure 4. - Radial-jet injectors.

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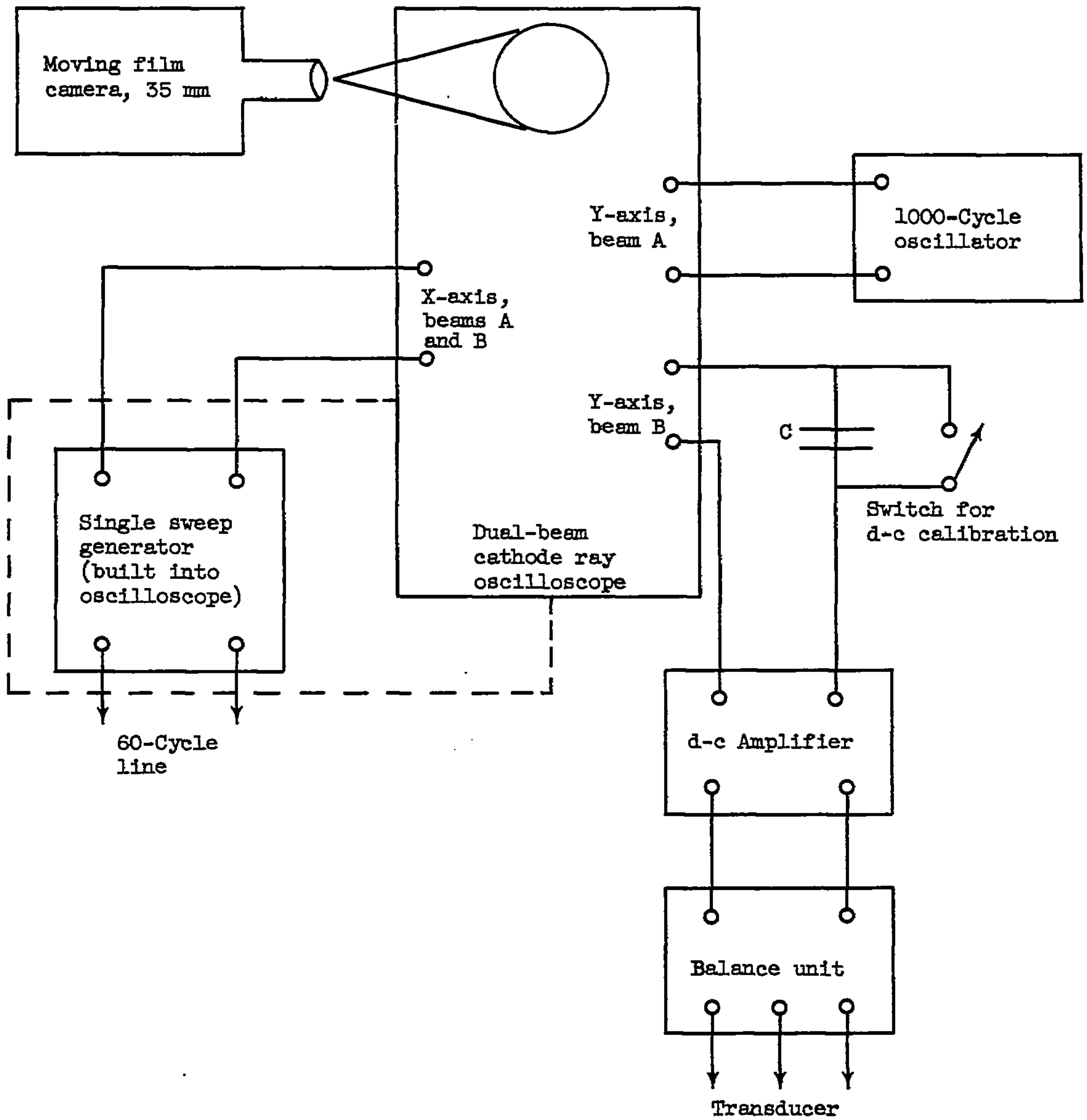


Figure 5. - Schematic diagram of circuitry associated with the high-frequency-response pressure transducer.

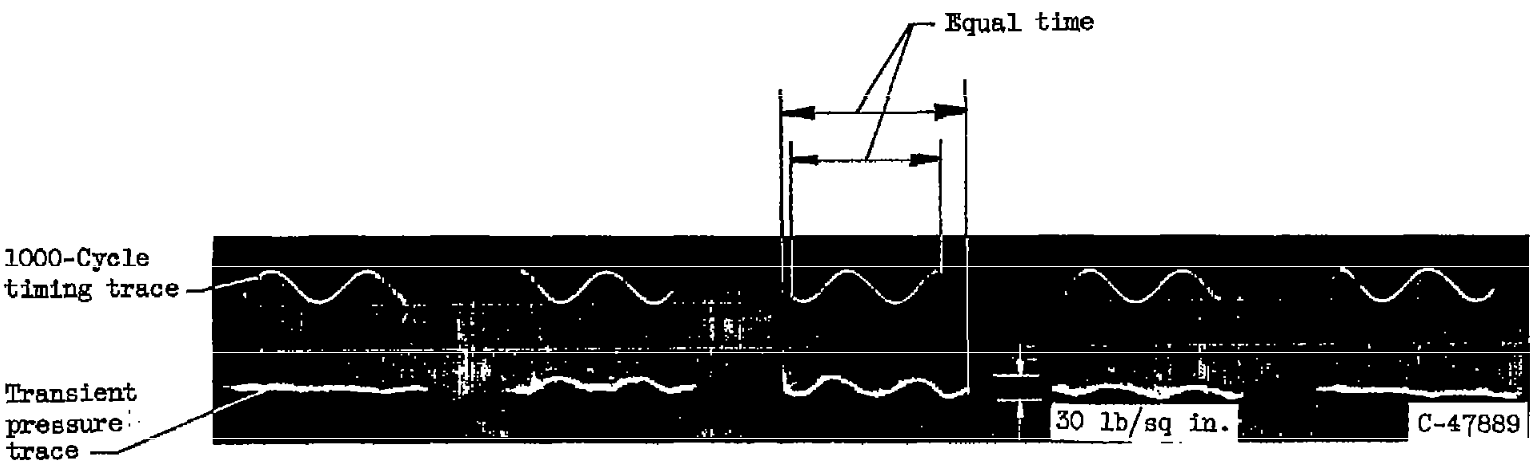


Figure 6. - Typical film sequence; experimental frequency, 1400 cycles per second; pressure oscillation amplitude, 30 pounds per square inch.

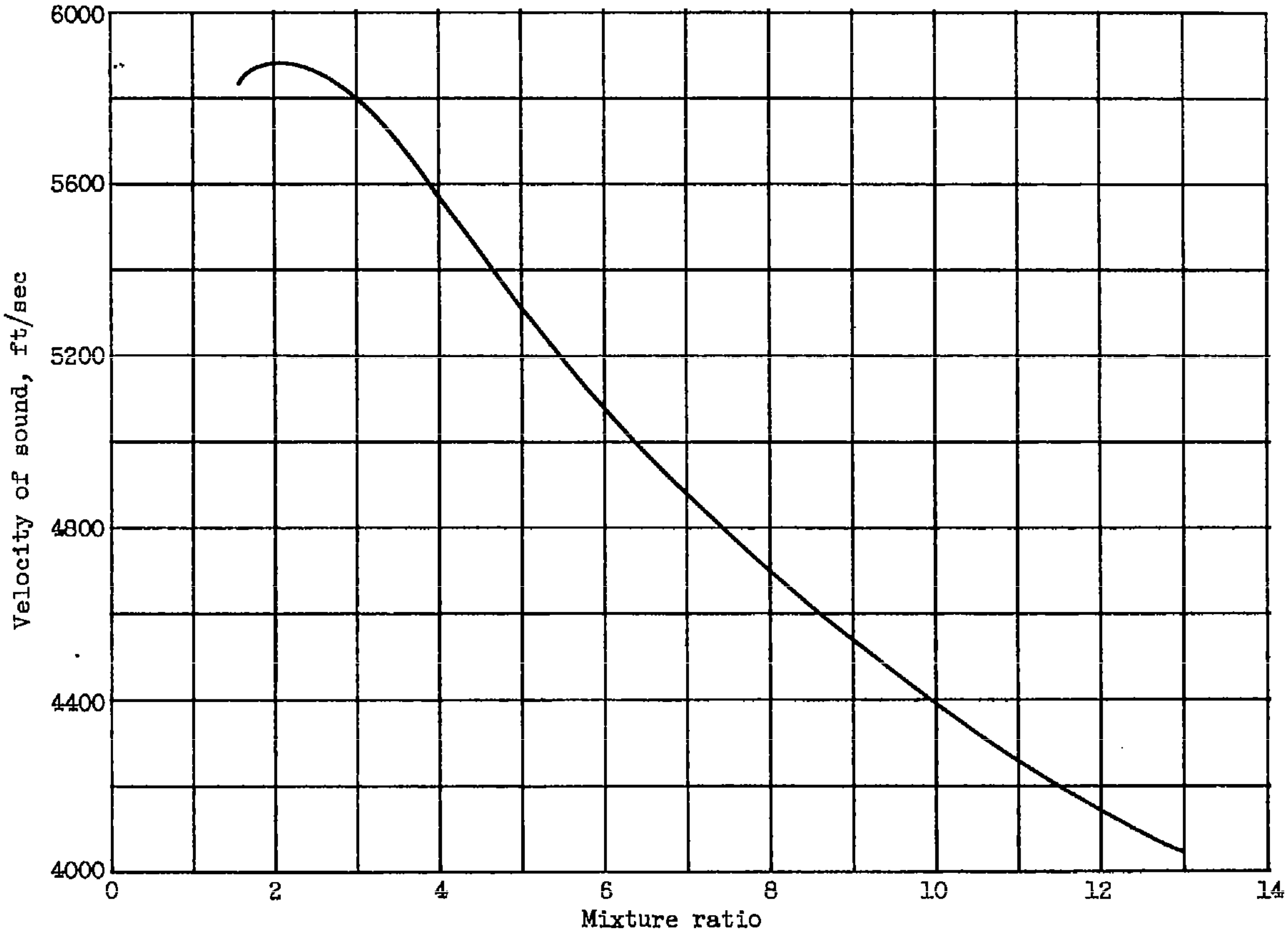
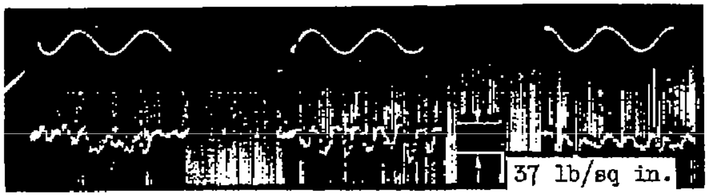
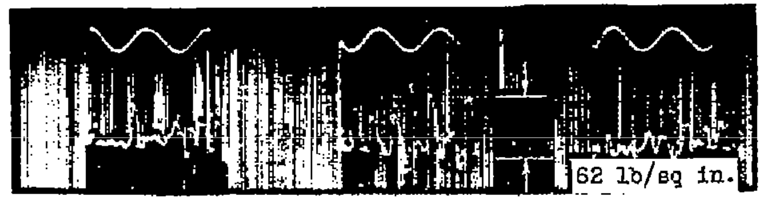


Figure 7. - Velocity of sound in adiabatic combustion products of liquid hydrogen and liquid oxygen as a function of mixture ratio.



Run 192; chamber length, 12 inches; mixture ratio, 3.11; experimental frequency, 3530; theoretical, fundamental longitudinal frequency, 2890.



Run 196; chamber length, 12 inches; mixture ratio, 6.92; experimental frequency, 3980; theoretical, fundamental longitudinal frequency, 2450.

(a) Nine-element, series II injectors.

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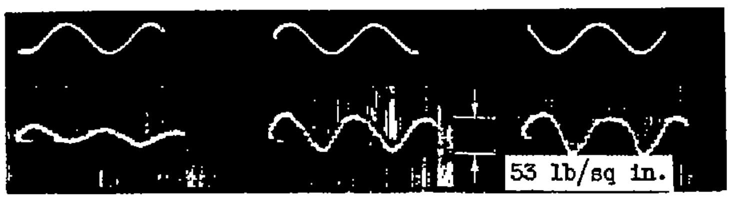
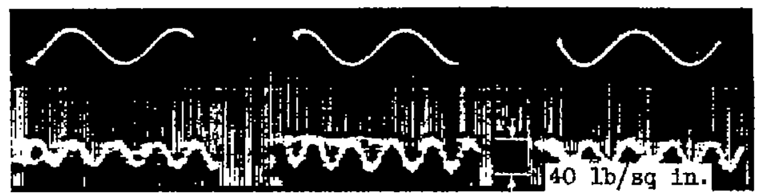


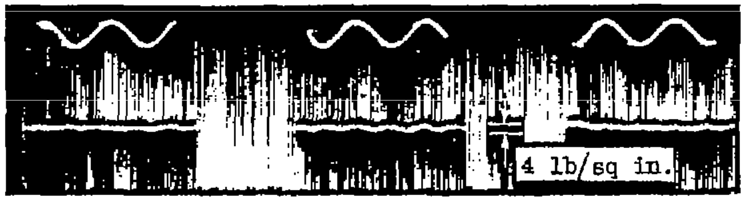
Run 281; chamber length, 24 inches; mixture ratio, 6.51; experimental frequency, 1400; theoretical, fundamental longitudinal frequency, 1240.



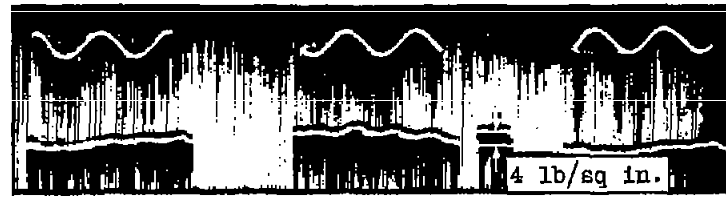
Run 267; chamber length, 12 inches; mixture ratio, 4.32; experimental frequency, 3100; theoretical, fundamental longitudinal frequency, 2800.

(b) Radial-jet injectors.

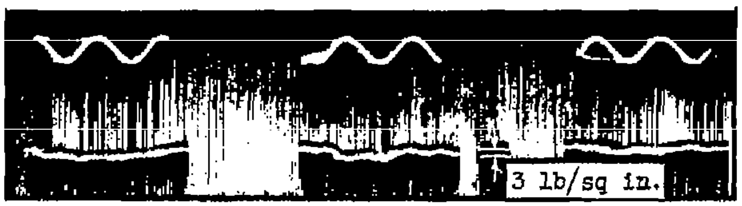
Figure 8. - Film strips from two runs made with injectors showing high-amplitude longitudinal oscillations.



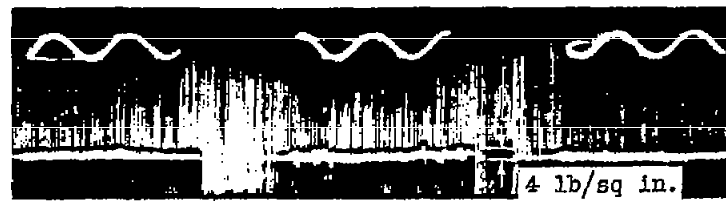
Run 90; chamber length, 14 inches; mixture ratio, 2.96; experimental frequency, 2470; theoretical, fundamental longitudinal frequency, 2490.



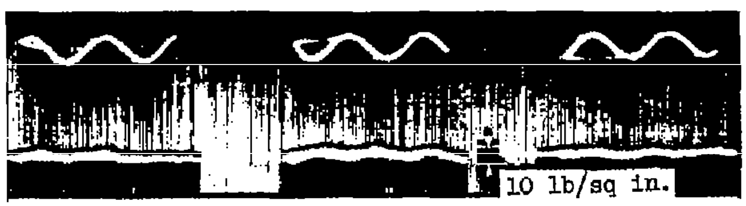
Run 92; chamber length, 14 inches; mixture ratio, 5.58; experimental frequency, 2200; theoretical, fundamental longitudinal frequency, 2220.



Run 97; chamber length, 14 inches; mixture ratio, 7.89; experimental frequency, 2050; theoretical, fundamental longitudinal frequency, 2020.



Run 101; chamber length, 22 inches; mixture ratio, 3.18; experimental frequency, 1730; theoretical, fundamental longitudinal frequency, 1440.



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Run 104; chamber length, 22 inches; mixture ratio, 4.68; experimental frequency, 1360; theoretical, fundamental longitudinal frequency, 1450.

Figure 9. - Film strips from five typical runs made with the series I injectors.

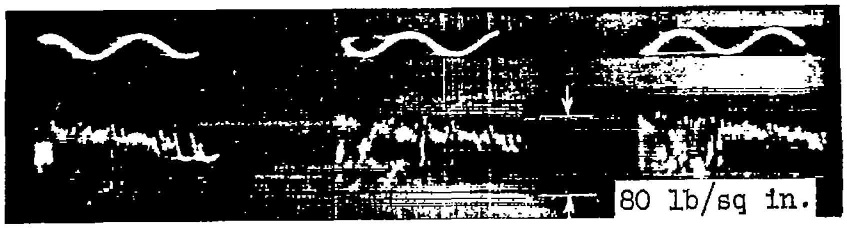

Figure 10. - Film strip from typical run made in 3-inch chamber showing very high-frequency irregular oscillations. Run 241; chamber length, 3 inches; mixture ratio, 4.71; experimental frequency, 34,500.

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Figure 11. - Film strip of run made with radial-jet injector in 3-inch chamber showing low-frequency oscillations. Run 274; chamber length, 3 inches; mixture ratio, 6.03; experimental frequency, 1250.

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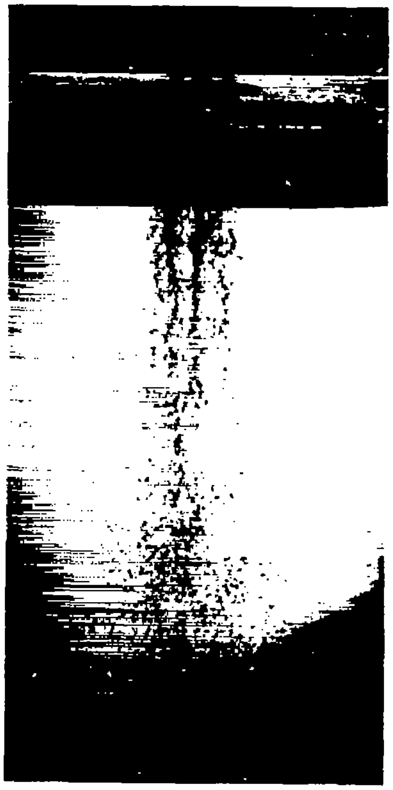

Series II, 30° impinging-jet, nine-element injector.

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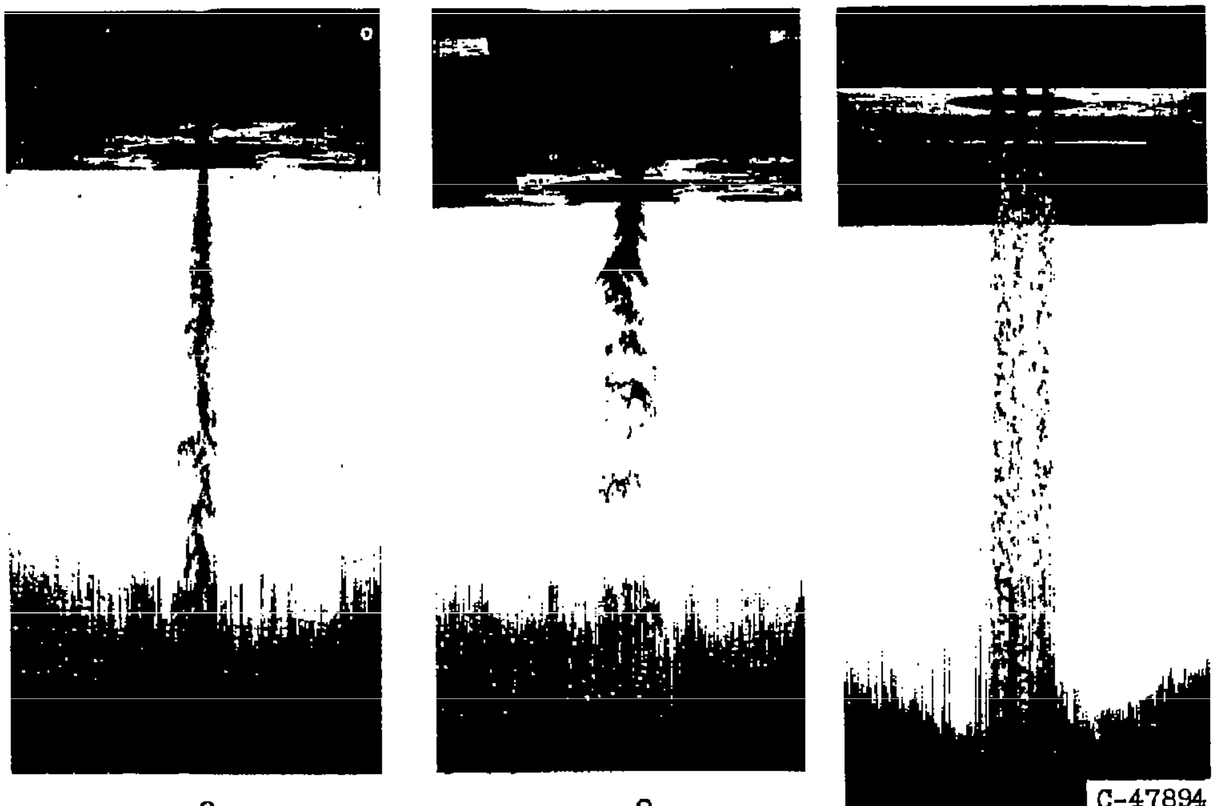
Spray photograph of radial-jet injector with 10-center-hole hydrogen-injection plate.

Figure 12. - Water-air spray photographs of injectors with which high-amplitude oscillations occurred.



Series II, 0° jets, single-element injector.

Series II, 40° jets, single-element injector.

Concentric-tube, nine-element injector.

Figure 13. - Water-air spray photographs of injectors with which high-amplitude oscillations did not occur.

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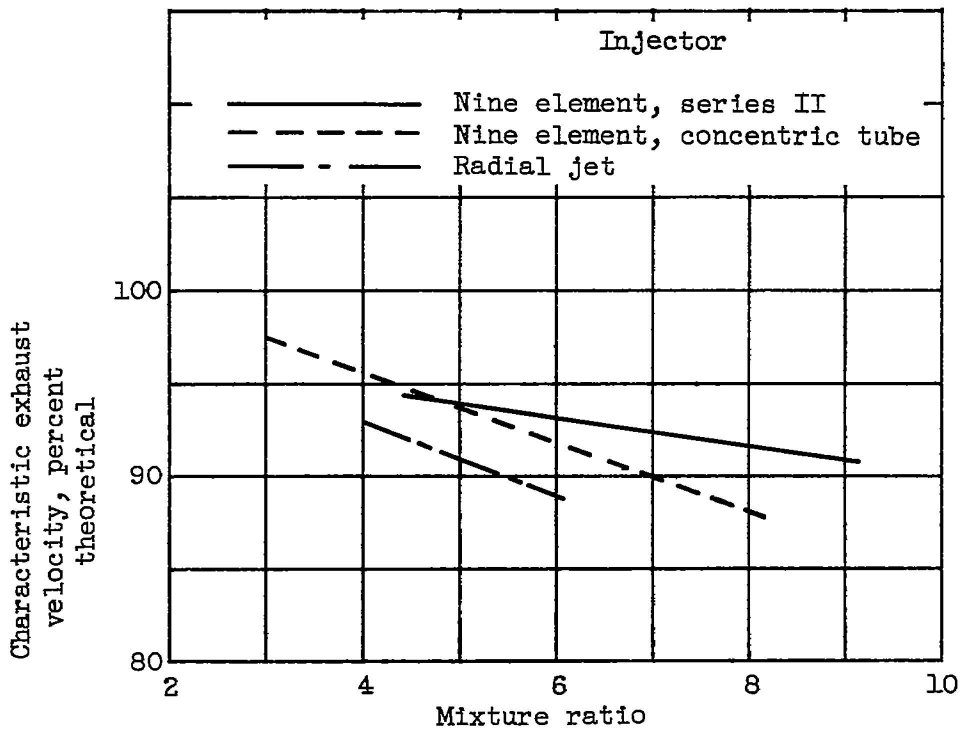

Figure 14. - Characteristic-exhaust-velocity efficiency as a function of mixture ratio in 3-inch chambers with three injector configurations.

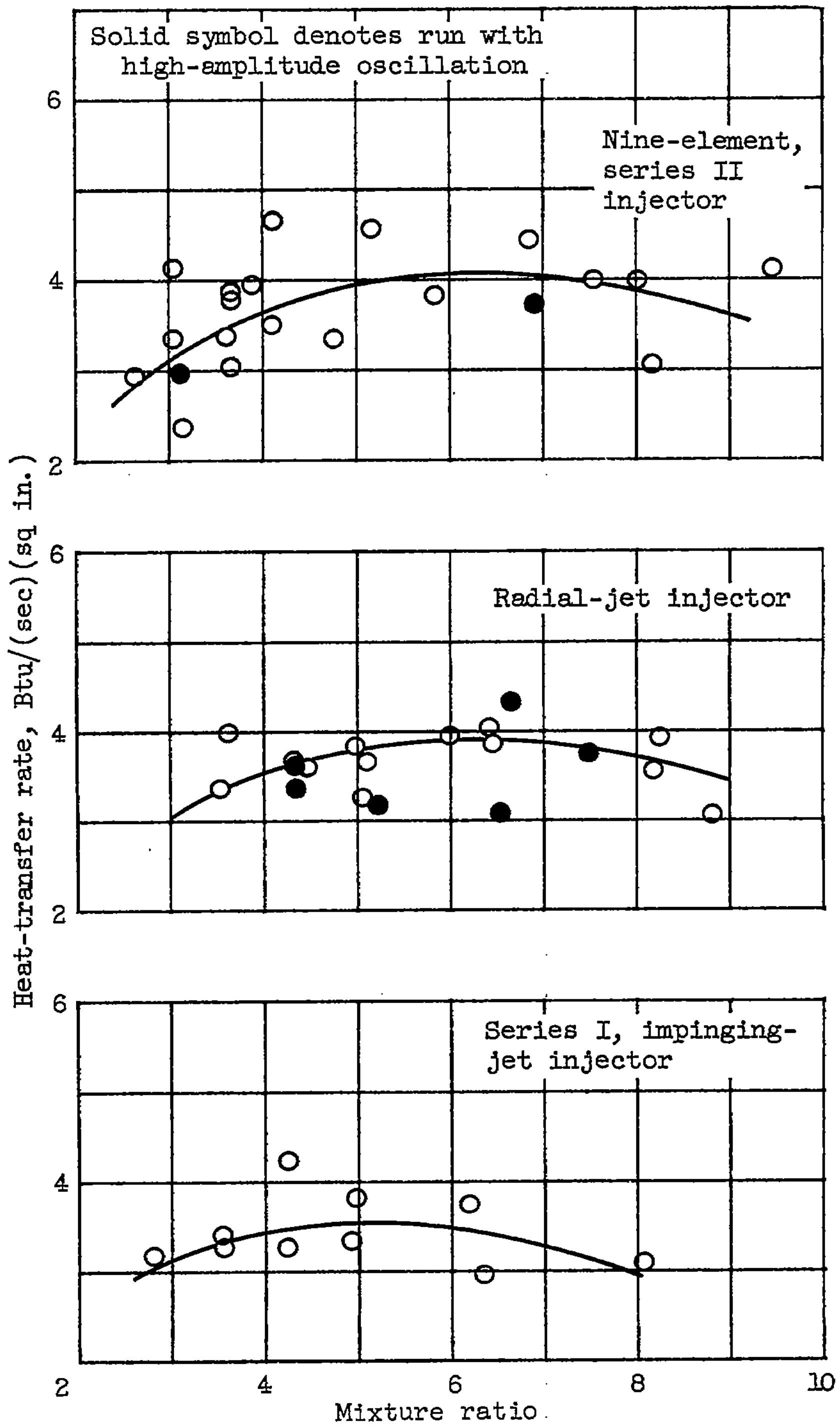

Figure 15. - Heat-transfer rate as a function of mixture ratio for three injector configurations showing screaming runs.

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